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Characterization of Cryogenic Mechanical Properties of Aluminum-Lithium Alloy C-458

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Mechanical properties of aluminum-lithium alloy C-458, which is one of the new generation alloys being developed for aerospace structural applications, were characterized. In light of potential applications of this alloy in future space launch vehicles, the effect of decreasing temperature down to 4K on the tensile and fracture properties were investigated. The tensile strength and the ductility increased at cryogenic temperatures, while the fracture toughness reduced slightly at 4K. This alloy was not sensitive to long-term low-temperature aging unlike some previous aluminum-lithium alloys. This may be attributed to the fact that the level of alkaline metal impurities in C-458 is substantially lower than those of other aluminum-lithium alloys.

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I. Introduction

C-458 is one of the new-generation aluminum-lithium alloys being developed to address anisotropy and other drawbacks of previous aluminum-lithium alloys. Many of the future space applications (satellite/ rocket components) under consideration for this alloy operate at temperatures well below room temperature; consequently, one focus of characterization in this study centered on the effect of decreasing temperature on the material properties of C-458. Another thrust was to evaluate any deleterious effects that could possibly result from long-term storage. Prior work has indicated that in previous-generation alloys, significant reduction in toughness occurs with extended aging (1,2). Exposure at 355K for 1000 h was chosen to simulate the effect of long-term storage.

II. Experimental Procedures

Alcoa provided C-458 plates used in this study in T861 condition (6% stretch followed by 24 h aging at 423K) in two thicknesses (45.7 mm and 19 mm). The composition of the delivered material as given by the supplier is listed in Table 1.

Tensile specimens were fabricated from the 19-mm plate with an overall length of 40 mm and a minimum cross-sectional thickness of 2.8 mm. Specimens were fabricated in both the longitudinal and transverse orientations and were machined from the center of the plate thickness. Fracture toughness compact tension specimens, also fabricated from the 19-mm plate, were 12.7-mm thick and 31.8 mm long in accord with ASTM E399 in L-T and T-L orientations. All samples were fatigue pre-cracked to within the tolerance set by ASTM E399.

Each configuration was tested in the following conditions using a standard Instron and the same cryogenic certified extensometer/clip-gage: room temperature, liquid nitrogen (77K) using a liquid-nitrogen submersion bath, and liquid helium (4K) using a vacuum canister and cryogenic feed. ASTM E1450-92 was used as the guide for the liquid-helium testing. Additional samples, taken from the same lot, were aged 1000 h at 355K. These samples were tested in the same temperature conditions as the original specimens. All samples were tested at a crosshead speed of 0.254 mm/min.

The standard 12.7-mm-thick compact tension specimens, machined from 19-mm-thick plate, did not meet the plain strain requirement for valid K_{IC} in this alloy. Larger compact tension specimens of

TABLE 1
Composition of Al-Li C-458

Comp	Cu	Li	Zn	Mn	Mg	Ti	Zr	Si	Fe	Al
Wt%	2.58	1.73	0.60	0.25	0.26	0.01	0.09	0.03	0.03	Bal.

38.1-mm thickness were machined from the 45.7-mm-thick plate in L-T orientation. Valid K_{IC} values of these specimens were compared to Chevron-Notch fracture toughness values of the 45.7-mm-thick plate. Chevron-notch specimens of 17.8-mm thickness were machined from the center of the plate in accord with ASTM E1304. Comparisons were also made between the 38.1 mm and 12.7 mm compact tension specimens. The Chevron-Notch samples were fabricated and tested in accord with ASTM E1304. The purpose of these tests was to compare the results of the two different methods for fracture toughness determination for this material as well as to quantify any differences between the 45.7 mm and 19 mm plate properties.

III. Results and Discussion

a. Tensile Properties

Tensile properties of C-458 T-861 before and after aging for 1000 h at 355K were summarized in Table 2. Each value is the average of three tests. Tensile strength and elongation data in the longitudinal direction were plotted in Figure 1. Transverse direction properties showed generally similar trends, with slightly lower values for both the strength and elongation.

As can be seen in Figure 1, the greatest value for yield strength and elongation of C-458 occurs at liquid-helium temperature. The increase in yield strength is approximately 20–25% in transitioning from room temperature to liquid-helium temperature. Ultimate strength, as expected, had the same trend with a 30% increase at liquid helium temperature. The variation between samples for yield and ultimate tensile data was less than 5% in every case with most test conditions near 1%. Elongation data had a larger variation, showing less than 10% variation in a majority of L-direction testing. The elongation in the T-direction had slightly larger changes, varying 10–20%. This can be attributed, in part, to the fact that some of the specimens fractured near the edge of the extensometer. The increases of the strength and ductility of C-458 at cryogenic temperatures are consistent with previous-generation aluminum-lithium alloys (3–5).

TABLE 2
Tensile Properties of C-458 T-861 before and after Aging for 1000 h at 355K

Direction	Temp (K)	T-861 YS	T-861 UTS	T-861 % Elong.	Aged YS	Aged UTS	Aged % Elong.
L	4	636.4	820.5	13.0	658.5	858.4	11.8
	77	596.4	696.4	12.5	643.3	746.7	10.2
	298	520.6	558.5	9.4	548.2	575.7	8.1
T	4	611.6	744.7	10.4	668.8	822.6	7.8
	77	565.4	679.2	9.7	639.2	727.4	9.2
	298	503.3	544.7	8.4	537.8	565.4	8.1

YS and UTS in MPa

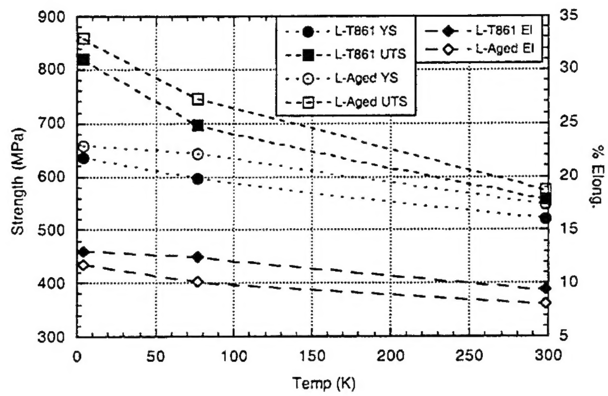

Figure 1. Plot of longitudinal tensile properties of C-458 at room and cryogenic temperatures.

Aging the C-458 resulted in an increased strength with a slight corresponding reduction in the elongation. This trend indicates that some age hardening is taking place at this low aging temperature even after T-861 treatment, suggesting that T-861 is not the peak temper. Scanning electron microscopy of the fractured surfaces indicated increased delamination at liquid-helium temperature as compared to room temperature for both T-861 and after aging.

b. Fracture Toughness

The fracture toughness of C-458 demonstrated an opposite trend to the tensile data. Toughness of the material in the T-861 condition decreased slightly in progressing from room temperature to liquid helium in both the L-T and T-L directions, with L-T having a higher value in each case. Aging for 1000 h at 355K did not change the fracture toughness in L-T orientation. Aged T-L specimens showed a slightly different trend. The fracture toughness for this condition did not change with decreasing temperature. Figure 2 contains the average value of the 3+ specimens tested at each condition. The variation of the data was 12% for the worst case, with most sample conditions ranging from 2–7%.

All specimens manifest increased delamination with decreasing temperature. This was readily apparent by observation with the naked eye as well as fractography with the SEM. Figure 3 shows the increasing delamination that occurs with decreasing temperature. This trend, when taken by itself, should cause the fracture toughness to increase as temperature decreased. It is interesting to note that within the delaminated layers there are regions of ductile fracture. This is seen most easily at room temperature and becomes less and less noticeable as the temperature is decreased. This trend can be

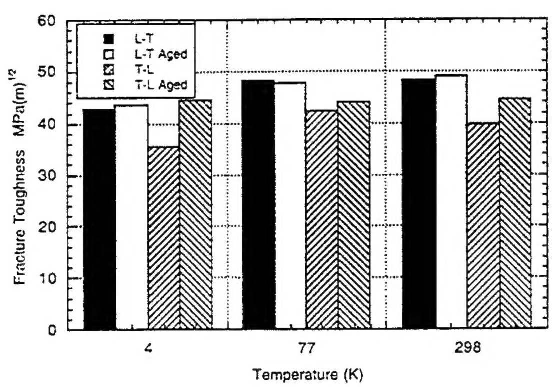

Figure 2. Compact tension fracture toughness of C-458 T-861 before and after aging.

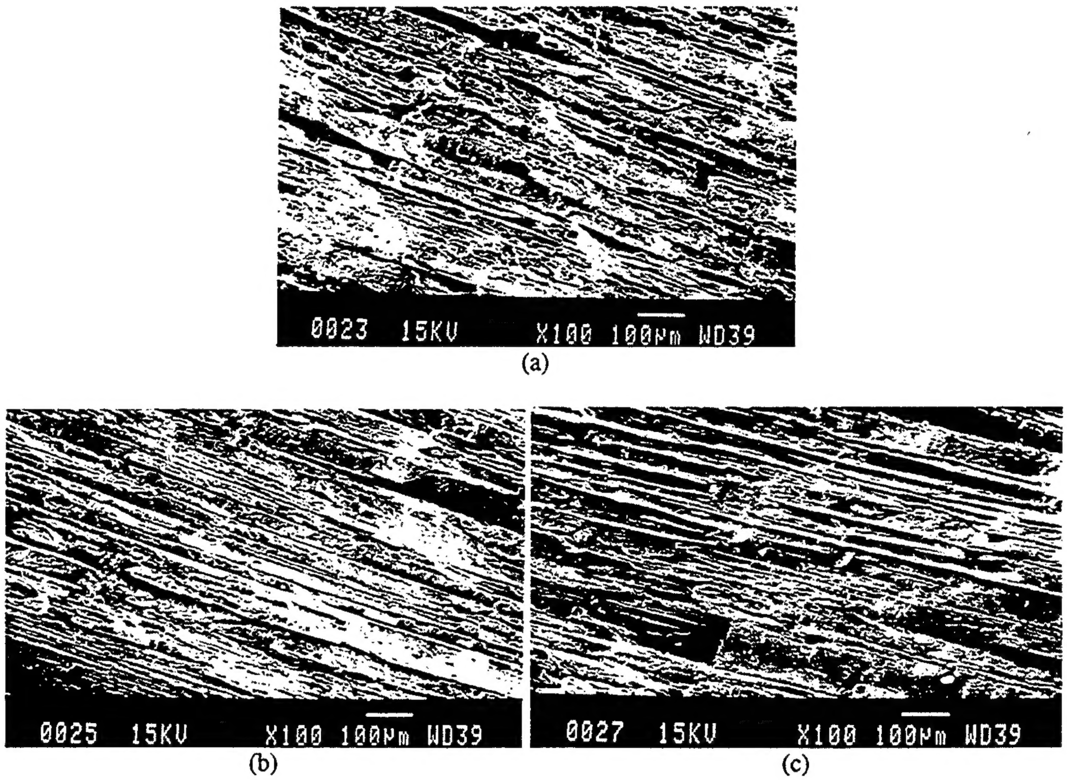

Figure 3. SEM fractographs of compact tension specimens of C-458 T-861. (a) Room temperature; (b) 77K; (c) 4K.

seen at a higher magnification shown in Figure 4, which shows dimpling in room-temperature fracture and more brittle laminar or plate-like fracture surface at cryogenic temperatures. This lessening in the ductile nature of the interlamination fracture could counter the toughening of the delamination and cause the observed decrease in fracture toughness at cryogenic temperatures.

There appears to be several mechanisms causing the observed changes in fracture toughness in C-458. On one hand, there is increasing delamination, a phenomenon that, when observed in previous alloys (3–7), was attributed to the strengthening of the material and resulted in increasing toughness. Conversely, there is a transition from a predominantly ductile fracture (microvoid coalescence) to a more brittle type fracture mode (transgranular shear) within the delaminated layers that should lead to decreased fracture toughness. The temperature effects also play a similar role in the localization of failure to the grain boundary as the grain interior is strengthened relative to the grain boundary (8), and may, in fact, be the cause of more brittle failure. A combination of these is the most likely reason for the observed slight decrease in the toughness in our study. Similar reduction in cryogenic toughness was also reported for 8090, 8091, and 2091 alloys (4) and 2095 (Weldalite 049) alloy (9).

Although many Al-Li alloys are known to have increased fracture toughness at cryogenic temperatures, it is apparently dependent on operating fracture mode. Alloy chemistry and test orientation can affect the operating fracture mode from room temperature to cryogenic temperatures, as can be seen in aforementioned references (4,9) and in our current study.

c. Alkaline Metal Impurities

Various studies have been performed on previous-generation aluminum-lithium alloys regarding the presence and effect of decreasing alkaline metal impurities such as Na and K (10,11,12). The effects

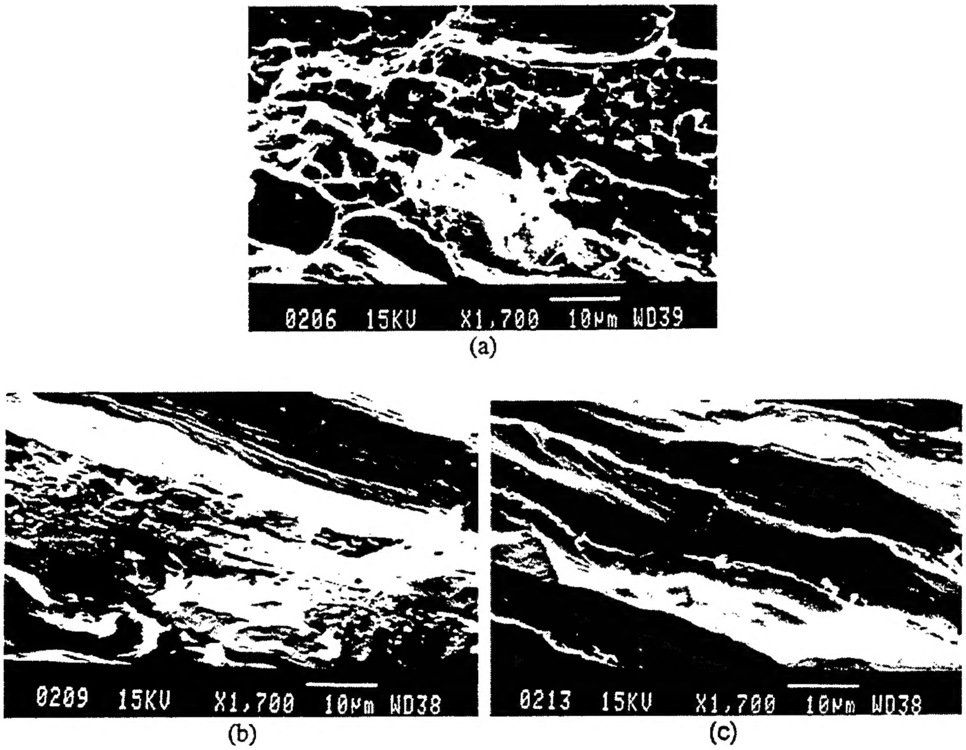

Figure 4. Higher-magnification fractographs corresponding to Figure 3. (a) Room temperature; (b) 77K; (c) 4K.

suggested range from decreasing toughness due to the formation of low-melting compounds in the grain boundaries with decreasing temperature to hydride formation at elevated aging temperature, which serves to toughen the material. C-458 shows no significant effect resulting from aging. This seems to indicate that if the problem in previous-generation alloys was due to alkaline metal impurities, then the amount of these impurities in C-458 has been reduced to a level that makes them a non-factor. Glow Discharge Mass Spectroscopy (GDMS) analysis of this material showed 1.9 ppm sodium and 0.4 ppm potassium. Al-Li 2195, a previous-generation alloy presently used in the NASA Space Shuttle external fuel tank, showed sodium content of 5.0 ppm and potassium content of <0.05 ppm. In our preliminary results of a similar aging study of 2195 alloy, the fracture toughness was reduced about 25 to 30% in S-L and about 10% in T-S after aging for 1000 h at 355K, both at room temperature and at liquid nitrogen. The S-L orientation would be more susceptible than the other orientations to the effects of aging due to the fact that it fractures in a peel mode. Nevertheless the data does demonstrate a definite degradation in toughness after low-temperature aging of 2195 alloy with a 5-ppm level of sodium impurity. The difference in content of the alkaline metal impurities between 2195 and C-458 may explain the different fracture toughness reduction after aging.

d. Chevron-Notch Fracture Toughness

Comparison of the chevron-notch toughness with the compact tension toughness of C-458 (samples fabricated from 45.7 mm plate) had predictable results. The value of fracture toughness for the chevron-notch specimens was approximately 5% higher than the compact tension. This is expected due to the initial conditions of each specimen (machined notch vs fatigue pre-crack). The average fracture toughness value for the chevron-notch was 44.9 MPa$\sqrt{m}$ compared to 42.8 MPa$\sqrt{m}$ for compact tension. The value for the compact tension samples can be compared to the data gathered on the 19 mm plate.

The value for comparison is 48.3 MPa$\sqrt{m}$. This difference was attributed to the combination of several factors. The 45.7-mm-thick plate may have slightly lower properties due to the differences in quench rate across the thickness and the amount of thermo-mechanical processing. The increased size of the specimen results in a valid plane-strain fracture toughness (K_{IC}), which should be lower than the Kq value measured for the 19-mm-thick plate. Due to smaller size requirement, the chevron-notch fracture toughness testing can be used to measure the plain-strain fracture toughness (K_{IC}) of 19-mm plate if we take a 5% correction factor as established in our test results.

IV. Conclusions

C-458 offers attractive properties for spacecraft and launch vehicle design. The toughness of the material is relatively high, and although there is some decrease at cryogenic temperature, the effect is not substantial. C-458, as demonstrated, is not sensitive to long-term low-temperature aging. This is an important improvement over previous aluminum-lithium alloys, which were prone to significant decrease in toughness with aging.

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